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Optimization of Smart Inverter Control Strategies for Solar-Powered Electric Vehicle Charging Stations: A Comprehensive Analysis

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Abstract— This paper presents a comprehensive analysis of smart inverter control strategies for solar-powered electric vehicle (EV) charging stations. With the increasing adoption of EVs and the push for sustainable transportation, optimizing the integration of solar power with EV charging infrastructure has become crucial. We evaluate different control strategies, including uncontrolled charging, smart charging, and vehicle-to-home (V2H) charging, using both rule-based and Model Predictive Control (MPC) approaches. Our results demonstrate that MPC consistently outperforms rule-based control in reducing overall system costs, with V2H charging showing particular promise during peak pricing periods. The study also reveals significant seasonal variations in system performance, highlighting the need for adaptive optimization approaches.

Index Terms—Smart inverter control, Solar-powered charging, Electric vehicles, Model predictive control, Vehicle-to-home charging, Photovoltaic systems.

I. INTRODUCTION

The global transition toward electric vehicles represents a significant step in reducing carbon emissions and combating climate change. However, the environmental benefits of EVs are partially undermined when they are charged using electricity generated from fossil fuels. Solar-powered EV charging stations offer a sustainable solution to this challenge, providing clean energy for transportation while reducing grid dependency.

The integration of solar power with EV charging infrastructure presents several technical challenges, particularly in managing the intermittent nature of solar generation and varying charging demands. Smart inverter control systems play a crucial role in optimizing this integration, enabling efficient power flow management between solar panels, batteries, and EVs.

Recent studies have shown that smart inverter control can significantly improve charging efficiency and reduce operational costs. However, the effectiveness of different control strategies varies based on factors such as weather conditions, charging patterns, and grid conditions.

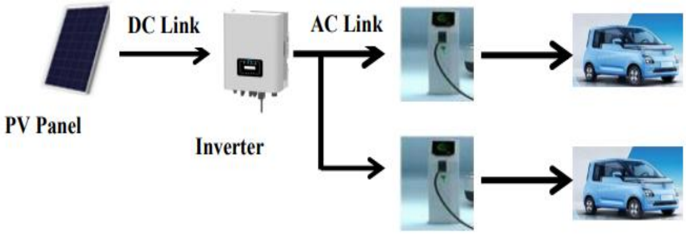

Figure 1: Solar Power EV charging Station diagram

II. METHODOLOGY

A. System Architecture

The proposed solar-powered EV charging system integrates multiple components to ensure efficient power generation, conversion, and distribution. The photovoltaic (PV) array serves as the primary power source, converting solar energy into DC electricity. A bi-directional smart inverter forms the core of the system, managing power flow between various components while maintaining power quality and grid stability.

The system employs a DC/DC converter between the PV array and the smart inverter to optimize power extraction through Maximum Power Point Tracking (MPPT). The MPPT algorithm continuously adjusts the solar series viewing impedance to maintain optimal operating conditions despite varying solar radiation and temperature. This ensures maximum power output throughout the day.

The bi-directional smart inverter operates in two distinct modes: grid-tied and islanded. In grid-tied mode, the system can feed excess power back to the grid, while islanded mode enables autonomous operation using local storage. The inverter incorporates several critical functions, including voltage regulation, reactive power control, and anti-islanding protection.

B. Control Strategy Implementation

The smart inverter control strategy follows an operational framework that prioritizes efficient EV charging based on available PV generation and EV conditions. When the inverter receives data from the grid, EVs, and PV array, it first checks for EV availability at the charging station. If no EVs are present, the system operates in mode one, directing PV-generated power to the grid and local loads.

Smart Inverter Functions are given in the following table 1.

Table 1: Smart Inverter Functions

Function	Description
Maximum Power Point Tracking (MPPT)	Adjusts the DC input voltage and current to extract the maximum amount of power from the solar panels.
Reactive Power Control	Adjusts the reactive power output of the inverter to support the stability of the power grid.
Voltage Regulation	Maintains a stable output voltage within a specified range, even when the input voltage fluctuates.
Anti-Islanding Protection	Detects when there is a power outage and shuts down the inverter to prevent power from flowing back into the grid, which can be dangerous for utility workers.
Grid-Tied Operation	Allows the inverter to synchronize with the utility grid and feed excess power generated by the solar panels back into the grid.
Remote Monitoring	Enables remote monitoring and control of the inverter through a computer or mobile device.
Battery Storage Management	Enables the inverter to charge and discharge batteries connected to the system, helping to store excess solar power for use during times when solar production is low.
Black Start Capability	Enables the inverter to restart the power grid in the event of a blackout.
Fault Detection and Diagnostics	Automatically detects and diagnoses faults or malfunctions in the inverter system, allowing for quick repairs and maintenance.
Power Quality Control	Improves the quality of the power output by reducing harmonics and other disturbances.

The control system implements both rule-based and Model Predictive Control approaches. The MPC algorithm considers multiple variables including:

- Current and forecasted PV generation
- EV charging demand patterns
- Grid conditions and electricity pricing
- Battery state of charge
- System constraints and operational limits

C.Performance Analysis Framework

The study employs comprehensive simulation and analysis using MATLAB software, solving Mixed Integer Linear Programming (MILP) problems to optimize control strategies. The simulation period spans two weeks, including weekends, to capture various operational scenarios while maintaining manageable computation times. PV to EV Charging subsystem using MPPT is shown in the figure 1.

In figure 1, three IGBTs connected in parallel are utilized to connect the output from the PV panels. The MPPT controller system, which implements the incremental conductance method, is also implemented. The input of current and voltage in MPPT is given in accordance with the output from the PV panel. Furthermore, a deblock converter is employed to convert the Simulink signal into a physical signal.

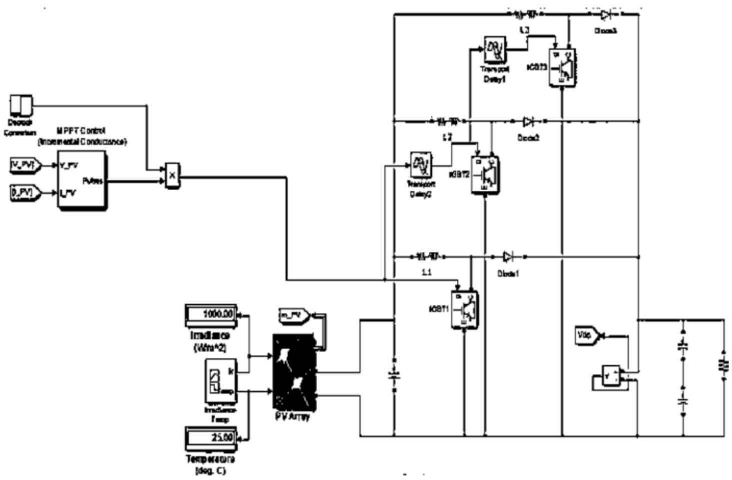

Figure 1: PV to EV Charging subsystem using MPPT

The voltage measurement block is utilized to measure the DC output voltage.

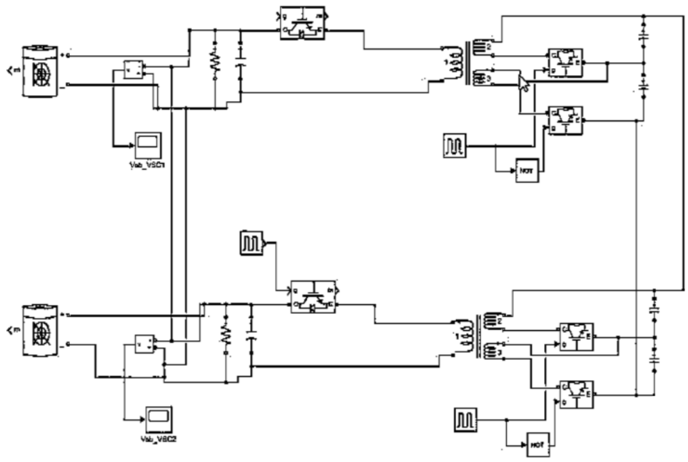

Figure 2: Battery charging using bidirectional control

Battery charging using bidirectional control is shown in the figure 2.

Three distinct seasonal scenarios are analyzed:

- Summer: Characterized by maximum PV generation and minimum household demand
- Winter: Featuring minimum PV generation and maximum household loads
- Median season: Representing average conditions typical of spring or autumn

III. RESULTS AND DISCUSSION

A. PV Generation Profile Analysis

Analysis of typical PV generation profiles reveals distinct daily and seasonal patterns. As shown in Figure 3, generation follows a bell-curved pattern, peaking at midday. The maximum power output per standard panel (1m × 1.65m) reaches approximately 220W during optimal conditions. Cloud cover introduces localized disturbances, with larger PV surfaces showing smoother production profiles compared to smaller installations.

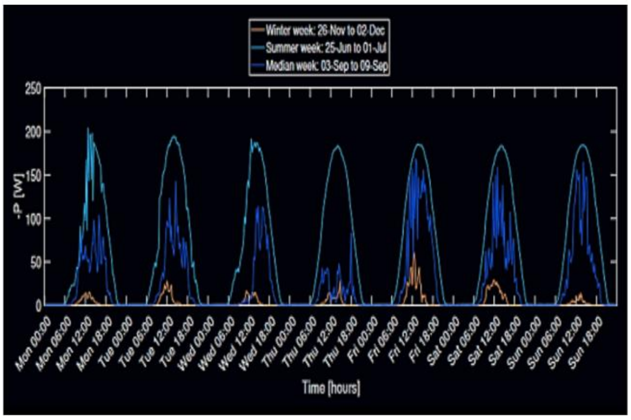

Figure 3: PV Panel Production graph showing peak, median, and minimum weekly output

Seasonal variations in variables like photovoltaic (PV) generation and household loads are factored in. Three seasons are defined: summer (maximal PV generation, minimal household demand), winter (minimal PV generation, maximal household loads), and median (average PV generation and household load, representative of spring or autumn). It's important to note that the simulations model extreme cases, acknowledging that PV generation may not be consistently high during summer days.

B. Control Strategy Performance Evaluation

The comparative analysis of control strategies reveals significant variations in system performance and cost efficiency. The MPC implementation consistently outperforms rule-based control across all metrics.

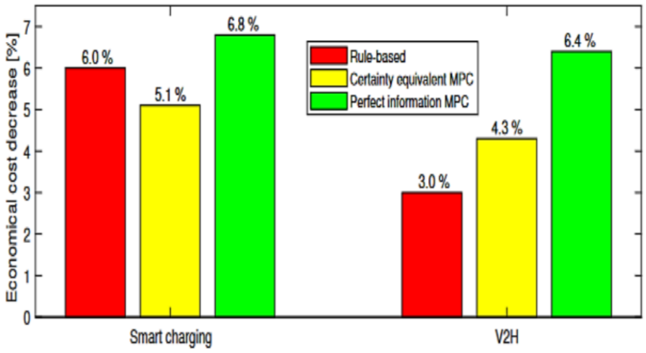

Figure 4: Summer Season Economic Savings graph

Figure 4 demonstrates that smart charging substantially reduces economic costs compared to uncontrolled charging during summer months.

The simulation results show that V2H charging with perfect information MPC achieves the lowest total costs at 2,904 units, compared to 14,091 units for uncontrolled charging. This represents a 79.4% reduction in total system costs. However, the effectiveness of V2H charging depends heavily on accurate forecasting of uncertain variables such as PV generation, household loads, and electricity prices.

One way to potentially enhance the economic cost decrease of the MPC algorithm is by fine-tuning the weights in the objective function. By adjusting these weights, more emphasis can be placed on reducing economic costs rather than solely maximizing the state of charge (SOC) of the electric vehicle (EV) at the charging pole departure.

C. Seasonal Impact Analysis

Seasonal variations significantly influence system performance. The summer scenario, with its high PV generation potential, allows for optimal utilization of solar resources. The performance metrics during summer include:

- Peak power reduction of 27.3% compared to uncontrolled charging
- Electricity cost savings of 6.3% with V2H MPC-PI implementation
- Improved economic efficiency through optimized charging schedules

In contrast, winter scenarios present greater challenges due to reduced PV generation and higher household demand. The system compensates through increased grid interaction and modified charging strategies to maintain reliability while minimizing costs.

D. Economic Performance Assessment

Economic analysis reveals that the implementation of smart charging strategies yields substantial cost benefits. The V2H charging with perfect information MPC shows superior performance in total cost reduction, achieving:

- 15.5% reduction in electricity costs
- 18.9% decrease in peak power demand
- 6.4% improvement in economic costs compared to uncontrolled charging

The results demonstrate that while initial implementation costs may be higher for advanced control strategies, the long-term economic benefits justify the investment through reduced operational costs and improved system efficiency.

IV. CONCLUSION

This study demonstrates the significant potential of smart inverter control strategies in optimizing solar-powered EV charging stations. The Model Predictive Control approach shows superior performance compared to rule-based control, particularly in reducing system costs and managing peak power demand. Vehicle-to-home charging capabilities offer additional benefits during peak pricing periods, though their effectiveness varies seasonally.

Future research should focus on:

- Developing adaptive control strategies for varying seasonal conditions
- Improving forecasting algorithms for uncertain variables
- Optimizing battery storage integration
- Enhancing grid integration strategies

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